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A Review of Recovery Boiler Model Applications

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A REVIEW OF RECOVERY BOILER MODEL APPLICATIONS

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ABSTRACT

Recovery boiler computer models were used to study black liquor combustion. These simulations combine three-dimensional computational fluid dynamics (CFD) calculations, with single particle and char bed black liquor combustion models to simulate the furnace combustion zone. Several boilers were studied using these simulations and the results are reviewed in this paper.

RECOVERY BOILER MODEL

Three-dimensional recovery boiler simulations have been used at IPST since 1987. Details of IPST's recovery boiler model development and some applications have been reported in references (1-5). To improve our understanding of the furnace combustion processes, the computer model has been applied to a number of operating boilers over the past two years. This paper will review the results of these modeling studies to analyze the status, as well as the usefulness of the recovery boiler model.

The recovery boiler model consists of three main components:

1. A computational fluid dynamics (CFD) component describing gas flows and heat transfer
2. An in-flight black liquor combustion model describing the trajectories and combustion of droplets
3. A char bed model

The combustion models are at a stage of development where they can be used with a commercial CFD code in two different ways to predict recovery boiler behavior. In the first method, gas temperature is assumed to be constant (isothermal) and the gas flow patterns are solved based on the inlet gas velocities. The in-flight combustion model is solved by using the fixed gas flow field and assuming constant gas concentrations. The char bed model is not included in the isothermal model. In the second method, the three models are solved simultaneously (fully-coupled) and the temperature is computed.

The more sophisticated fully-coupled (non-isothermal) method takes considerably more computer time: 14 days versus 2 days for isothermal (on an IBM RISC 550). However, non-isothermal simulations provide more information, such as temperature and gas concentrations. In the application of the computer model, the isothermal approach has been used for the bulk of the simulations to minimize computational time. This simplified approach still provides much data on the boiler operation, including gas flow patterns and black liquor drop trajectories. In addition, a fully-coupled simulation has been carried out to verify results and to examine temperature and concentration fields.

Isothermal Gas Flow Model

Gas velocity patterns in the 3-D recovery boiler model were calculated using the commercial CFD program Fluent ver. 4.23. A Cartesian grid design was used for the isothermal models, which creates a stair-stepped char bed geometry (ref. 5). With this simple type of grid, the resulting velocity data can easily be imported into the in-flight black liquor combustion model for the simulation of particle trajectories and combustion behavior. The overall grid size used for these models ranged from 35,000 to 150,000 cells.

The In-flight Combustion Model

Velocity data, calculated from flow field model, are imported into the in-flight combustion model. Except for the velocity data, conditions in the furnace were assumed to be uniform. At each of the black liquor gun ports the boiler operating conditions are used to specify the initial liquor conditions (solids-% and temperature). A distribution of liquor drop sizes, initial directions and velocities are also specified.

The trajectory and combustion behavior of each drop are then calculated individually and sequentially. In this model the black liquor consists of four components, water, volatiles, char and smelt, which correspond to the processes of drying, pyrolysis and char burning (6). The black liquor combustion model determines the rate of drying, de-volatilization, and char burning, based on the heat and mass transfer rates for the individual drops. The model provides information on the distribution of these mass transfer processes throughout the furnace. The fates of the combustible part of black liquor (volatiles and char) can be used to analyze boiler operation. For good reduction efficiency and bed control, the proper balance between suspension burning and bed burning needs to be maintained. The final fate of the drops can also be determined, i.e., whether it hit the wall, landed on the char bed, or was carried-over. One measure of boiler plugging tendency is the predicted carry-over (particles that are entrained with the gas stream at the outlet of the furnace).

Fully-coupled Model

The fully-coupled recovery boiler model has three major components: a CFD code for gas flow, heat transfer, and gas phase reactions; an in-flight particle model for particle trajectories and combustion in air; and a char bed model for combustion, sulfate reduction and temperature distribution in the char bed. The three components exchange information iteratively so that the results of one submodel will affect the others. A body-fitted coordinate (BFC) version of Fluent was used for CFD purposes and the black liquor combustion submodels were developed at IPST.

RECOVERY BOILER #1

Recovery Boiler #1 experienced plugging in the upper furnace heat transfer tubes, that caused frequent boiler shut-downs. Past efforts to reduce plugging had resulted in poor combustion efficiencies and high emission levels. The objective of this study was to use a recovery furnace computer model to gain a better understanding of key factors that affect physical carry-over of black liquor ash for this recovery boiler.

Isothermal CFD Model of Boiler Gas Flows

This is a small boiler with five secondary ports on each side wall and two secondary ports on the front and rear walls. The tertiary air system has 2 front ports and 3 rear ports (interlaced). The boiler is a B&W sloped bottom design and the char bed is a moderate sized mound-shaped bed that rises to about the secondary air port level. To simplify the CFD calculation, the lower furnace zone was simulated with a flat base and stair-stepped bed as a boundary for gas phase flows. A flat boundary condition at the top of the furnace was specified as the bullnose.

In order to maximize the resolution of the main combustion zone and air port specification, the furnace was specified with a vertical plane of symmetry running from the front to rear wall through the center of the boiler. The roughly 25 individual primary air ports on each wall were specified as a continuous slot with the appropriate width to conserve mass and momentum of the incoming primary air stream. Secondary and tertiary air ports were specified as individual air inlet streams. To maintain the correct momentum and mass flow into the furnace, the model air ports were enlarged to compensate for the lower density. The CFD specification of the boiler required 35,075 nodes.

Figure 1 shows an isometric view of the boiler boundary conditions. The boiler is oriented so that the front of the boiler (the outlet side) is on the left and the rear (bullnose) is on the right. This same isometric orientation is used in all of the subsequent flow figures. Because of the plane of symmetry only half of the boiler is shown. The CFD grid geometry is shown in Figure 2.

Contour plots characterizing the flow fields, as computed by the Fluent CFD program, are shown in Figure 3 for the base case (#1-A). The base case flow field used the standard operating conditions for the boiler with an air distribution of 60%:29%:11% (primary:secondary:tertiary). This figure displays the vertical velocity component for five horizontal slices. The most important feature discovered in the flow field results was that the two close secondary ports on the rear wall combined to form a single jet with a high degree of penetration. This combined with the three tertiary jets on the rear wall and tended to create a high velocity flow channel near the front wall, which could entrain droplets right around the bullnose.

It was hypothesized that the secondary air port arrangement might not be optimal due to the squeezing effect of the predominantly two side wall arrangement. This caused large upward flows at the front wall near the liquor gun. For this reason it was suggested that the secondary air distribution be reduced by 9% and distributed to the primary and tertiary level (where an oversized fan could handle the additional capacity). This was the basis for the second air distribution scheme of 65%:20%:15% (case #1-B - Figure 4). The chimney appears somewhat reduced in Figure 4, with a more uniform vertical velocity profile. Despite this apparent improvement in the flow field, combustion studies do not support a move to this air distribution because of higher carry-over predictions.

Black Liquor In-flight Combustion

This boiler has two liquor nozzles located on the front and rear walls of the boiler. The parameters investigated in this study were black liquor drop size (2.5mm vs.

1.5mm median drop diameter), and horizontal firing angle (-15°, -30°, -45°). Each of these six conditions was simulated in a factorial design with the two different air distributions described above.

The firing temperature of black liquor has only a small effect on droplet size until the flashing temperature is reached. At this point the drop size distribution in the spray becomes unstable as water in the black liquor evaporates and the median drop size decreases dramatically. The mill black liquor firing temperature of 245°F (67% solids) is near the flashing temperature, so that drop size may be very sensitive to liquor temperature.

The base case simulation for the #1 boiler was based on an assumed flashing condition with Dm=1.5mm. In order to simulate the effect of lowering black liquor firing temperature, a non-flashing spray was specified with a Dm of 2.5mm. It is the median droplet size that has the greatest effect on black liquor combustion and entrainment. The base case simulation was based on a firing angle -30° below horizontal. This is a relatively large downward angle compared to many boiler operations. A steeper downward firing angle and an angle closer to horizontal were also simulated in this study.

Gas phase temperature was specified as 1000°C throughout the combustion zone. Concentrations are typical of average conditions in the combustion zone (5% O_2, 20% H_2O, and 12% CO_2). These conditions could be in error near air ports and near the surface of the bed, but these values are relatively good assumptions for bulk conditions.

Carry-over Results

One of the main predictions desired was that of carry-over. A listing of carry-over predictions for each combustion simulation is presented in Table 1. This table can be used to make some preliminary observations.

1) Although the flow field #1-B appeared slightly more uniform, carry-over was always higher for flow field #1-B than #1-A. The highest carry-over occurred when smaller droplets were injected at -15° horizontal angle (nearly 20% of ash is entrained).

2) Drop diameter was the firing variable with the most impact on carry-over. A reduction of firing temperature to non-flashing conditions (Dm=2.5mm) resulted in substantially reduced carry-over predictions. One of the biggest differences in combustion behavior between the flashing and non-flashing cases is that more black liquor mass reaches the bed un-combusted in the non-flashing case. Clearly the smaller drops burn in-flight to a larger degree, resulting in less char that goes directly to the bed.

3) Firing angle had a significant effect on combustion and carry-over and could potentially be used to optimize operation if black liquor temperature were reduced. A more thorough investigation of firing angle would be required to optimize this variable. It is interesting that the effect of firing angle differs between the two flow fields, and that the simulations with the highest and lowest levels of carry-over occurred with a -15° firing angle.

Spray Angle Theta	Carry-over (% of smelt) Dm= 2.5	Dm= 1.5
	Flow Field #1-A	
-15°	0.13%	1.28%
-30°	0.51%	2.18%
-45°	0.44%	1.24%
	Flow Field #1-B	
-15°	5.52%	19.59%
-30°	1.98%	8.59%
-45°	1.70%	7.37%

Table 1. Particle Carry-over - Recovery Boiler #1

RECOVERY BOILER #2

The main objectives of this study were to help determine the reason the boiler was plugging frequently and to explore improved air delivery and black liquor firing practices. Boiler #2 is a large, relatively new boiler.

Isothermal Gas Flow Calculation

Four different boiler operating conditions were simulated in this phase of the project. At the beginning of the study, the mill was operating with a high gas flow-rate to the tertiary jets (40% of the total flow). Later the mill returned to a more traditional gas flow arrangement with less tertiary air (20%). The mill was also interested in examining a "swirling" type of gas flow. In this design three secondary ports on the right side of each wall were closed up to impart a swirling motion to the air at the secondary level. For each of the two operating cases described above, a swirling air design was also tested, resulting in a total of four flow fields (listed in Table 2).

When this study began, the air distribution to boiler #2 was 30%:30%:40% (primary:secondary:tertiary) or about twice the conventional tertiary air levels. Although reduction efficiency and emissions were not a concern, the boiler was plugging more frequently than normal.

If simulations of high tertiary (#2-A, Figure 5) are compared with conventional tertiary (#2-B, Figure 6) more uniform velocity profiles in the upper furnace are found for the high tertiary case. For low tertiary, the upward velocity is higher at the liquor gun level, because there is more total air introduced (80% vs. 60%) below the guns. In this case (#2-B), the high velocity region also extends into the upper furnace, since the tertiary air is not sufficient to break-up the high velocity core. In the upper part of the furnace before the superheater section, uniform velocity (and temperature) profiles are preferable for good boiler operation.

Air Level	Velocity (m/sec)	%Flow (%)
#2-A High Tertiary Non-Swirling		
Tertiary	40.9	40%
Secondary	34.0	30%
Primary	15.3	30%
#2-B Low Tertiary Non-Swirling		
Tertiary	34.2	20%
Secondary	50.7	45%
Primary	17.7	35%
#2-C High Tertiary Swirling		
Tertiary	40.9	40%
Secondary	43.8	30%
Primary	15.3	30%
#2-D Low Tertiary Swirling		
Tertiary	34.2	20%
Secondary	65.2	45%
Primary	17.7	35%

Table 2. Inlet Gas Flow - Recovery Boiler #2

Uniform velocity profiles also reduce physical carry-over so it follows that there should be less carry-over in the high tertiary case. This was what the isothermal simulations showed: very low carry-over for the high tertiary mode. This would suggest that the high plugging tendency reported by the mill was not caused by physical carry-over. Chemical analysis of deposit samples indicated that the plugging deposits were fume related.

Swirling air distributions and firing practices

Alternative air delivery and black liquor firing strategies, using a swirling air flow pattern, were investigated using computer simulations. Blocking secondary ports on the same side of each wall (right-hand corners) created significant rotation of flow (swirl) in the lower furnace. The simulations showed that swirl helps reduce carry-over since drops are pushed to the walls by centrifugal forces (Table 3).

However, the swirling action also changed the combustion behavior in the lower furnace by changing the distribution of black liquor. For example, much less char is burned in-flight and more char strikes the walls. This could have a dramatic effect on the overall boiler operation. Carry-over was highest for the low tertiary non-swirling air distribution (#2-B) and was also sensitive to drop size. Smaller drop sizes always led to increased physical carry-over, regardless of the air distribution.

Mass Distribution of Black Liquor Dm=2.5mm			
Case	Comb char	Hit Wall char	Char Bed char
Hi 3° Non-swirl	0.7807	0.1353	0.0841
Lo 3° Non-swirl	0.7955	0.1248	0.0797
Hi 3° Swirl	0.6824	0.2261	0.0916
Lo 3° Swirl	0.6168	0.3189	0.0639
	Hit Wall smelt	Char Bed smelt	Carry-over smelt
Hi 3° Non-swirl	0.3979	0.6017	0.0004
Lo 3° Non-swirl	0.5652	0.4294	0.0054
Hi 3° Swirl	0.7763	0.2225	0.0000
Lo 3° Swirl	0.8756	0.1219	0.0000

Table 3. Final Distribution of Black Liquor Components - Recovery Boiler #2

Conclusions

Computer simulations show that physical carry-over is unlikely for the high tertiary case (30:30:40). Physical carry-over is more likely to occur for a conventional air distribution (35:45:20). Carry-over is sensitive to drop size; small drops were carried out to a large degree, large drops were not carried out. Flashing of the liquor (high firing temperatures) will cause a high degree of carry-over which could lead to plugging in the superheater section.

Computer simulations show that swirl patterns reduce carry-over for both high tertiary and conventional air distributions but increase the amount of liquor striking the walls. This method should be tried cautiously since simulations show a drastic change in air flow patterns near the bed and lower walls.

RECOVERY BOILER #3

The main goal of this study has been to use a computer model to help determine optimal long-term operating strategies for this recovery boiler. A meeting was held at the mill to define specific objectives. The scope of work was limited to: 1) define a base case that is as close to the normal operating conditions as possible using recommendations from the boiler manufacturer, 2) look for potentially sensitive variables which could cause problems as boiler operation is adjusted, and 3) examine the issue of changing boiler load between 70% and 100% of design in terms of air delivery and the number of liquor guns and location.

Isothermal Flow Model

This is a very large recovery boiler with four separate air levels instead of the three levels used in traditional furnace designs. Inlet air port conditions were based on a design air flow-rate at 100% of the maximum continuous rating (MCR) and a constant gas density (0.267 kg/m3). Additional model simulations were performed based on 70% of MCR.

Results at 100% of Design Load

A "five finger" (three front, two rear) interlaced tertiary air port arrangement was used in all simulations. In the first flow field (Case #3-A) the air distribution was primary -35%, low secondary -40%, high secondary - 9.5% and tertiary -15.5%. All of the primary, low secondary and high secondary ports were used in this model.

Several variations on air delivery at 100% load were studied, but most of the changes to the base case conditions did not result in improved flow fields. The operating conditions that gave the best results are for case #3-B. Three changes were made to the base case to arrive at this improved flow field. First, the air flow at the low secondary level was reduced from 40% to 31% by closing two ports in each corner. Second, three start-up burners at the high secondary level were used to increase air flow at the high secondary level (from 9.5% to 17%). Finally, the air flow-rate (and the inlet velocity) at the tertiary level was increased from 15.5% to 17.0% of the total air.

Flow Fields at 100% of Design Load

The resulting flow fields for the base case (Case #3-A) are shown in Figure 7. The ports at all four air levels can be seen in this graph, along with the black liquor gun ports (3 per wall). A high velocity central-core region can be observed below the tertiary jets. The tertiary jets dissipate the high velocity core. A high velocity central core in the lower furnace is a common feature of recovery boilers, and can result in increased levels of physical carry-over if it extends into the upper regions of the furnace.

Case #3-B, also at 100% load, shows the effect of changing the port and air distribution, while maintaining the same total air flow-rate (see Figure 8). The core that forms above the secondary level is somewhat broader than in the base case. As in the previous case, the core is broken up by the tertiary jets. There are small remaining regions of higher velocity along both the front and back walls of the furnace. The velocity profile in the upper furnace is slightly more uniform for Case #3-B than for Case #3-A. This is due to a weaker core just above the secondary ports and higher tertiary velocities. Overall both of these cases resulted in what appear to be "good" flow patterns, with no obvious problems.

Combustion at 100% of Design Load

Three mass median drop sizes (2.0, 3.0 and 4.0mm) and three gun angles (0, 10 and 20 degrees below horizontal) were used for a total of nine in-flight combustion simulations with the base case flow field. At each of 12 nozzles, 30 drop diameters, and 17 individual angles were used, representing a total of over 6000 unique drops per simulation. The drop diameters are calculated from a square-root normal distribution based on the mass median diameter (7).

The fates of the combustible fractions of black liquor (volatiles and the char as shown in Figure 9) has been used to analyze predicted boiler operation. For good reduction efficiency and bed control, the proper balance between suspension burning and bed burning needs to be maintained. To minimize the boiler plugging tendency, predicted carry-over should be minimized.

The initial drop size had a strong influence on the amount of combustibles reaching the char bed. With a 2.0mm mass median drop size almost all the burning occurred in-flight and only about 1% of the combustible material reached the char bed. At 3.0mm about 11% of the combustibles and at 4.0mm about 30% of the combustibles reached the char bed. The variables that control the drop diameter (nozzle pressure and BL temperature) will have a significant impact on the char bed behavior.

The downward angle of the splash-plate nozzle had a weak effect on the fate of the black liquor components. As expected, increasing the downward spray angle resulted in slightly more combustible material reaching the char bed. At 3.0mm, changing the angle from 0 to

-20 degrees increased the amount reaching the bed from 11% to 18%.

The flow field simulations reveal a uniform vertical velocity in the upper furnace, indicating that physical carry-over should not be a problem in this boiler. The results from the in-flight model confirm this. In all of these simulations, only smelt was found to be carried over, with all the other liquor components being combusted. Figure 10 shows that the mass fraction of the smelt carry-over was 1% or less for both of the 100% load flow fields. Carry-over was sensitive to the flow patterns and was higher for the base case. The more uniform velocity profile resulting in Case #3-B helped reduce physical entrainment.

Results at 70% of Design Load

The computer model was used to study the effect of air distribution and black liquor firing practices at reduced loads. As the black liquor load to the boiler is reduced, it is necessary to reduce the total air flow. One option is to shut off the tertiary air when the load drops below 75% of MCR. An alternative approach is to maintain all four air levels while reducing the port area and flow-rate.

To compare the effect of these two options, additional testing was done at 70% of design load. In the first version (Case #3-C) tertiary air was not used so that more air was available at the three lower levels. All of the primary ports (90% open) were used. At the low secondary level, eight corner ports were closed completely and the remaining 32 ports were 75% open, and all eight high secondary ports were used. The second low load model (Case #3-D) used all primaries (80% open), 32 low secondary ports (75% open), 8 high secondary ports, and 5 tertiary ports (75% open).

Flow Fields at 70% of Design Load

The flow fields for Case #3-C, calculated at 70% of MCR without the tertiary air, are shown in Figure 11. The effect of not using tertiary jets can be seen in the persistence of the high velocity central core in the upper furnace. This caused higher carry-over. The upward velocity in the lower furnace was also somewhat higher since all the air was now injected at a lower level.

The use of tertiary air in Case #3-D significantly improved the air distribution and mixing in the upper furnace (see Figure 12). In the upper one third of the furnace the vertical velocity is quite uniform across the entire width of the furnace. Since this will increase the minimum retention time in the furnace, it should improve combustion efficiency.

Combustion Results at 70% of Design Load

Operation at low load means that either the size or number of nozzles has to be reduced to match the lower black liquor flow-rate. By maintaining the same liquor velocity (and temperature) through each nozzle, the initial drop size will remain constant. At 70% MCR, nozzle velocity is maintained by using either eight 24mm nozzles or twelve 20mm nozzles.

There are several ways to arrange these 8 black liquor guns, which affects the distribution of black liquor landing on the char bed. With three nozzles on the front and rear wall and a single nozzle on the side walls (3/3/1/1) the distribution of black liquor reaching the char bed is elongated in a direction parallel to the front wall. This suggests that the char bed would also have an elongated oval shape parallel to the front wall. The smelt ports for this boiler are located along the front wall, so this 3/3/1/1 layout should provide the most uniform delivery of smelt to the smelt spouts, and the best overall operation at 70% of design load.

The two flow field cases resulted in nearly identical distributions of combustible material. In general, the drops remain in the lower furnace and are not affected by the tertiary air. However, for black liquor particles that reach the upper furnace, the use of tertiary jets is important for minimizing carry-over. For the flow field where tertiary air was not used (and the high velocity core formed), the carry-over was twenty times higher for 2.0mm drops (see Figure 13). When tertiary air jets were used, the uniform velocity in the upper furnace almost eliminated carry-over.

Non-isothermal Model - Results and Discussion

A simulation (at 100% of the design load) was solved using the fully-coupled recovery boiler model. The fully-coupled recovery boiler model has three major components: a CFD code for gas flow; an in-flight model for particle trajectories and combustion; and a char bed model for combustion and sulfate reduction in the char bed. The three components exchange information iteratively so that the results of one submodel will affect the others. The results of this model provide a comparison with the isothermal flow field and in-flight model.

Case Setup

The geometry of the model was set up to match the actual boiler design and the isothermal model. The furnace is represented by a grid of $51 \times 51 \times 57$ (=148257) cells. The air flow-rates and inlet velocities match those used previously in the isothermal base case model (100% of design load). A fixed smooth char bed shape was specified in the model. Figure 14 shows a detail of the bed surface grid which is the interface between gas cells and char bed cells.

Liquor spray conditions match those used in the previous isothermal case. Two mass median drop diameters (Dm) were used to test the effects of drop size on combustion and carry-over. Except where specified, the results presented are for Dm=3.0mm.

Flow Patterns Results

Figure 15 shows the vertical velocity contours at different elevations. Overall, there is good agreement with the isothermal flow field results (compare Figure 7) and the same main features can be seen in both versions. There is an upward central core above the secondary air level. This is expected from the symmetrical arrangement of the primary and secondary air ports. The channel is broken by the strong interlaced tertiary air jets, resulting in a uniform flow pattern in the upper furnace.

Temperature

Temperature distribution is closely related to the combustion of volatile and char components of the black liquor. The temperature distribution shown in Figure 16 has a hot region in the center of the lower furnace. This hot region results, in part, from the combustion of volatiles released from the bed. The hot gas stream follows a flow pattern that shifts slightly towards the front wall as it continues up the furnace. The tertiary air jets effectively break the hot channel, resulting in a fairly uniform temperature distribution at the bullnose level. The predicted exit gas temperatures range from 1180 to 1270 K (about 900 to 1000 °C), which agrees well with the design value (about 1000 °C).

It can be seen that the temperature profiles correspond with the velocity profiles shown previously, i.e., the regions of high temperature in the upper furnace coincide with regions of high velocity. Therefore, a uniform velocity contour from an isothermal model may be a good predictor of a uniform temperature profile.

Particle Trajectories and Mass Distribution

Table 4 shows the fractions of black liquor that was released in different zones. Most of the volatiles were released to the gas phase, with a small portion landing on the bed. Half of the carbon is burnt in air, a third lands on the bed, and the rest hits the walls. Smelt is nearly equally split between the walls and the bed. A very small fraction of smelt (0.14%) is carried out of the furnace. The values calculated in this model are in good agreement with the values calculated for the same conditions with the isothermal in-flight model.

Zone	CH_4	Char	Smelt	Total
In-flight	93%	47%	0%	52%
Walls	0.5%	18%	53%	21%
Bed	6.5%	35%	47%	27%
Carry-	0%	0%	.14%	.05%
Total	100%	100%	100%	100%

Table 4. Black Liquor Mass Release by Zone

Effect of Drop Size

In addition to the 3.0mm Dm simulation, a 2.0mm Dm was also tested to examine the effect of drop size on combustion. Table 5 compares results for the two drop sizes. Drop size did not have a large influence on the average gas temperature leaving the furnace (at the bullnose). The biggest difference in simulation results was that the char bed temperatures differ by more than 200 °C. Since less combustible material is reaching the char bed with the smaller drops, the higher temperature may be due to the increased in-flight combustion above the char bed. Carry-over was also sensitive to drop size. Smaller particles resulted in significantly more carry-over. This is intuitive and consistent with the isothermal results.

	2.0mm	3.0mm
Max Gas Temp (°C)	1600	1570
Avg Exit Temp (°C)	939	944
Avg Exit O_2 (%)	2.6	3.1
Carryover (% smelt)	0.97	0.14
Max Bed Temp (°C)	1039	831
Avg Bed Surf Temp	835	603

Table 5. Effects of Drop Size on Operation

Conclusions

The operation of recovery boiler # 3 has been simulated using both an isothermal method and a fully-coupled (non-isothermal) modeling technique. Results from the fully-coupled method agree with isothermal simulations and support the validity of the fixed-field modeling technique that was used for most of this work.

At 100% of design load, both the isothermal and the non-isothermal models produced "good" flow fields with uniform velocities in the upper furnace. The non-isothermal case simulation gave a uniform temperature profile in the exit flow at the bullnose level, which should result in good superheater performance. The exiting gas temperature and O_2 concentration agree well with the design.

The three-front ports, two-rear ports interlaced tertiary air system was effective in achieving a well distributed air flow pattern with good mixing.

In general it does not appear that carry-over of black liquor drops will be a significant problem with this boiler, unless the black liquor firing conditions are producing very small drops. Mass median drop diameter was a critical variable for black liquor particle behavior. Increasing the drop diameter resulted in increasing amounts of combustibles reaching the char bed and decreasing levels of carry-over. The average gas temperature leaving the furnace, however, was not affected significantly by drop size.

Under low load conditions the use of tertiary air is beneficial. At 70% of design load the elimination of tertiary air allows the formation of a high velocity central core which persists into the upper furnace. Simulations showed that the use of tertiary air breaks up the central core and creates a uniform vertical velocity in the upper furnace. As a result, the carry-over tendency was greatly reduced.

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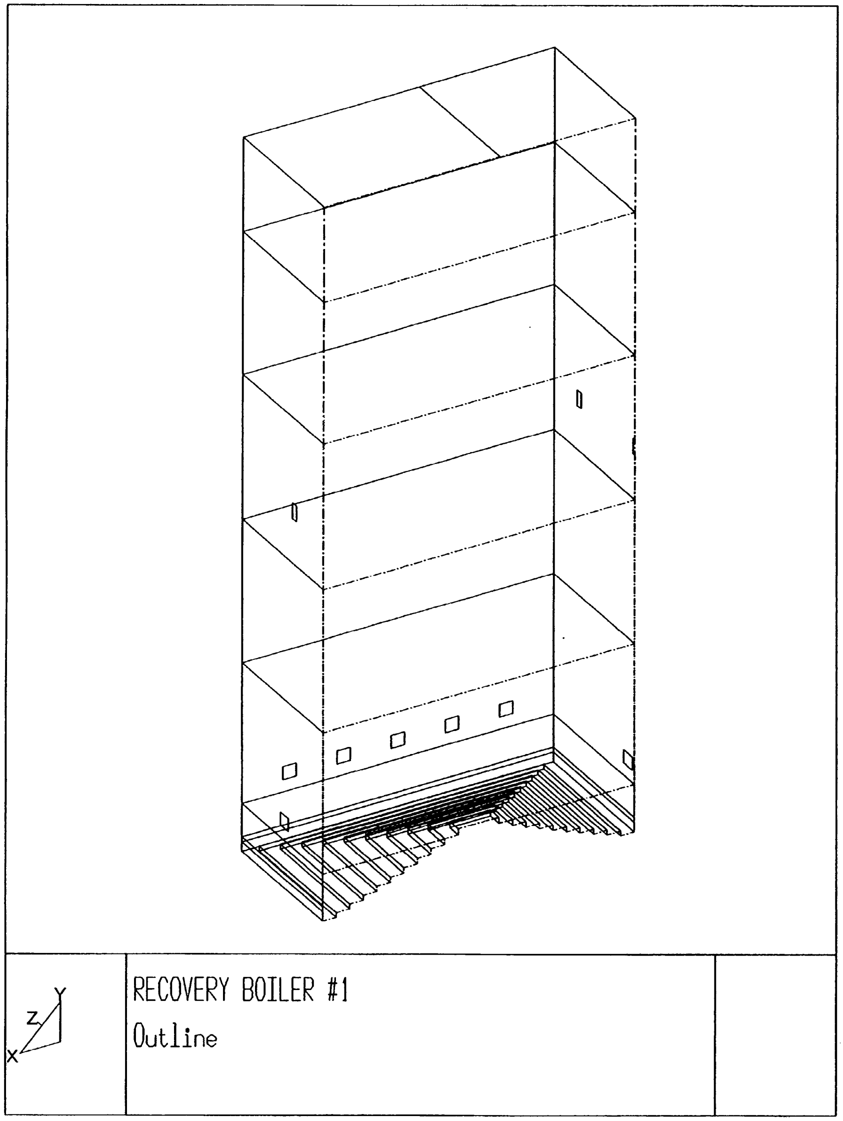

Figure 1 Recovery Boiler #1

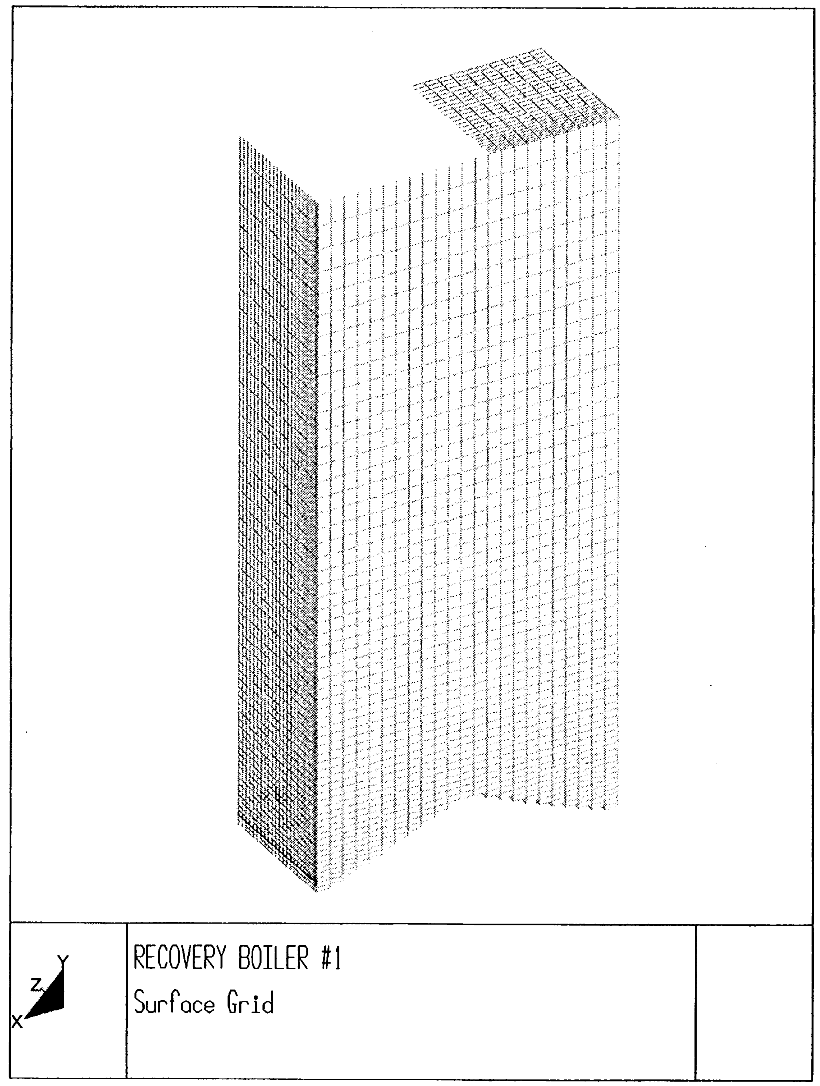

Figure 2 Recovery Boiler #1 - Grid

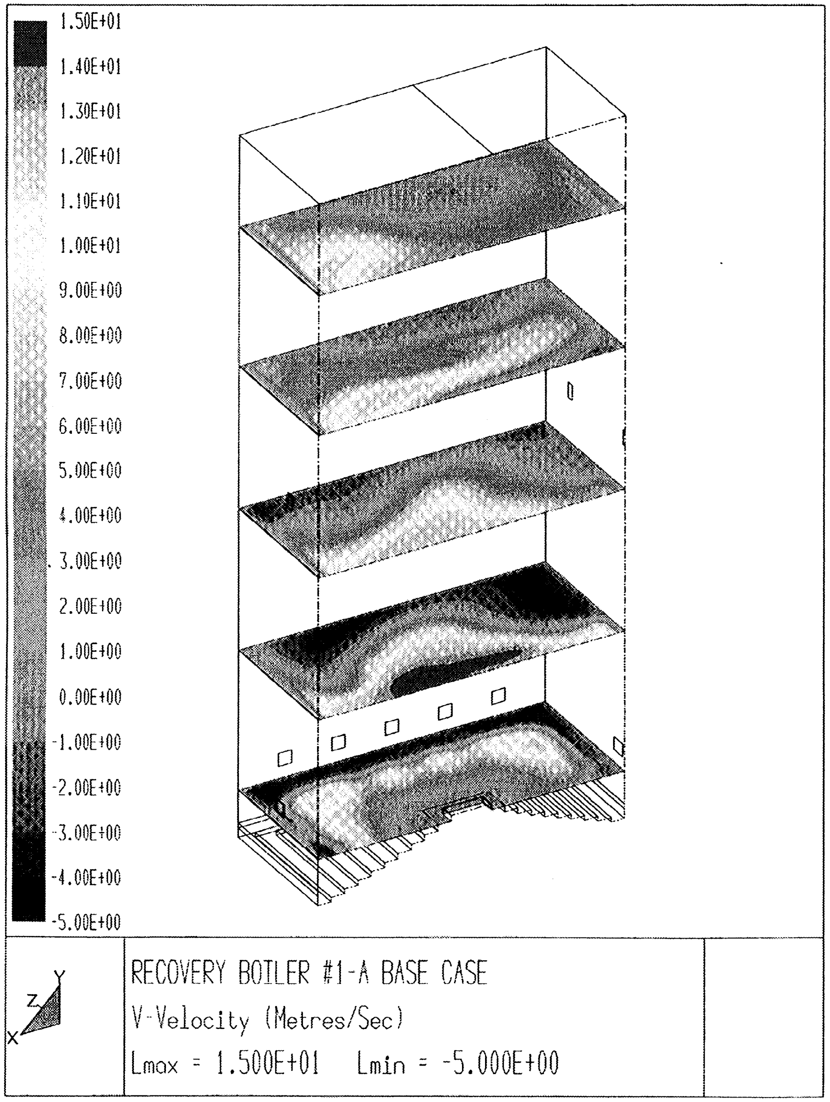

Figure 3 RB #1-A - Flow Field

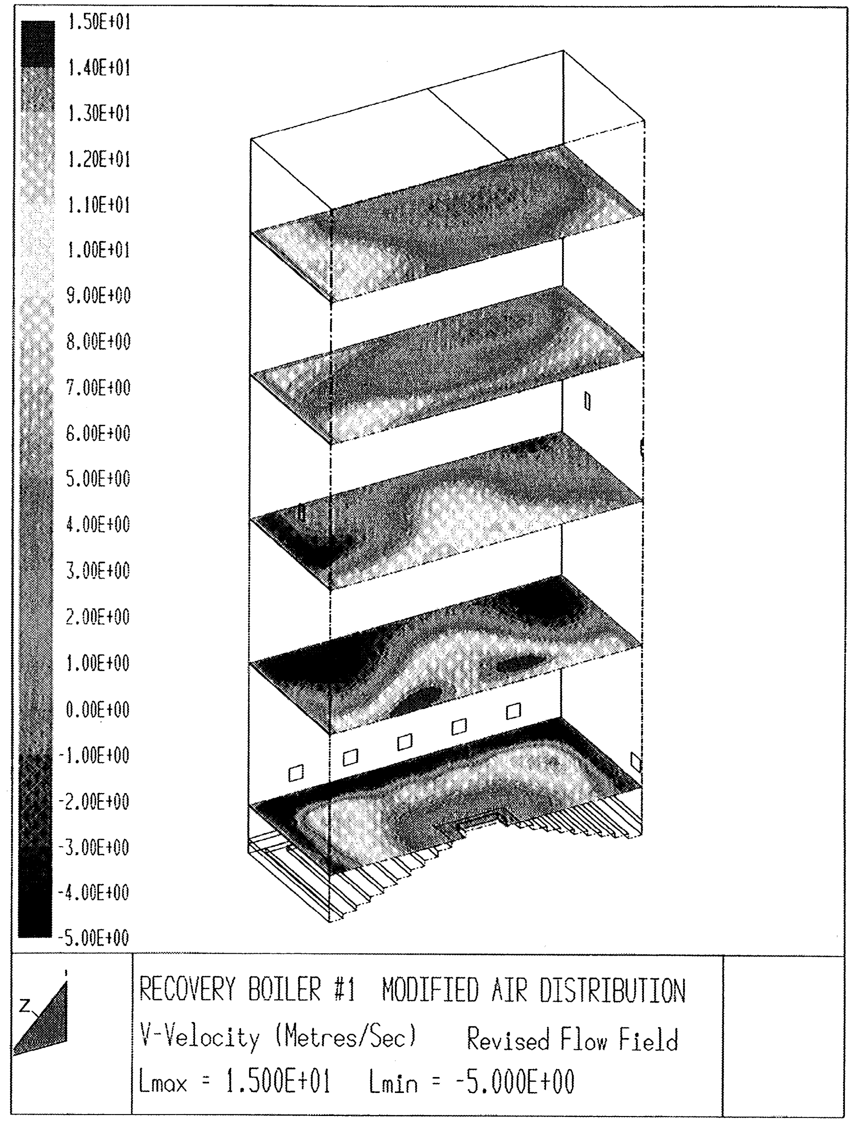

Figure 4 RB #1-B - FLow Field

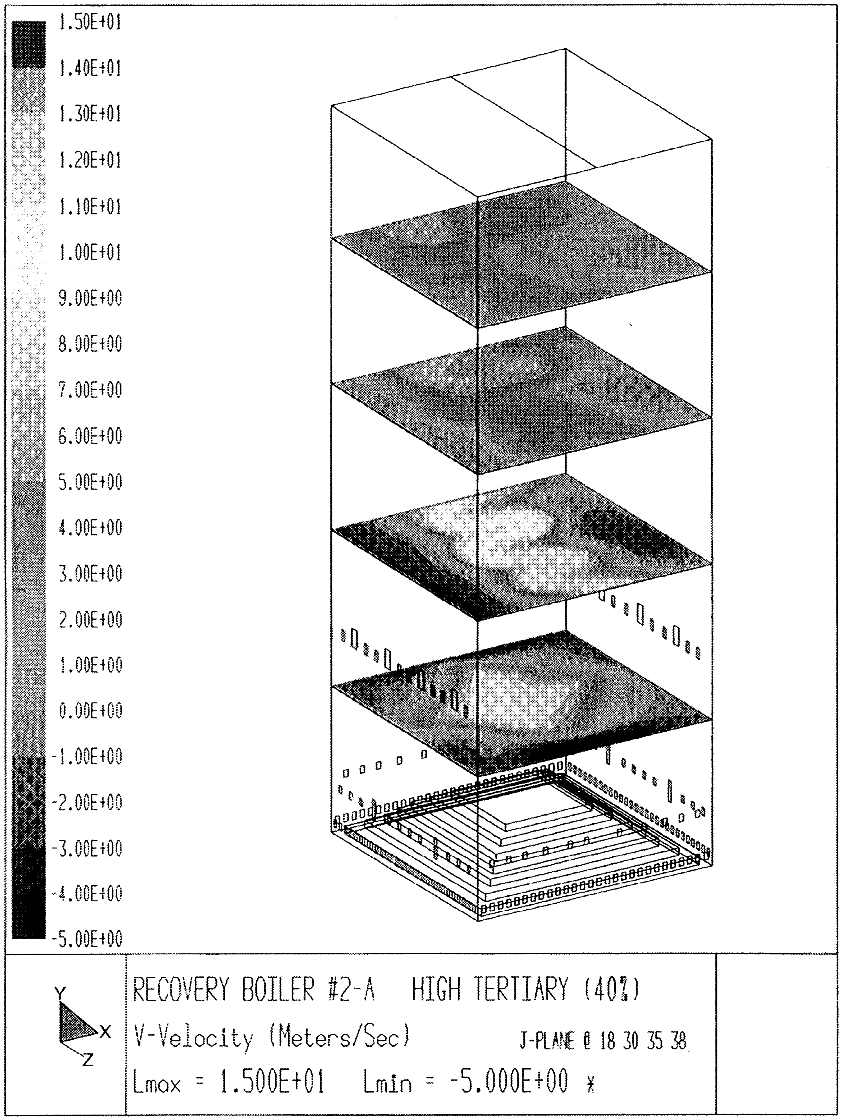

Figure 5 RB #2-A - Flow Field

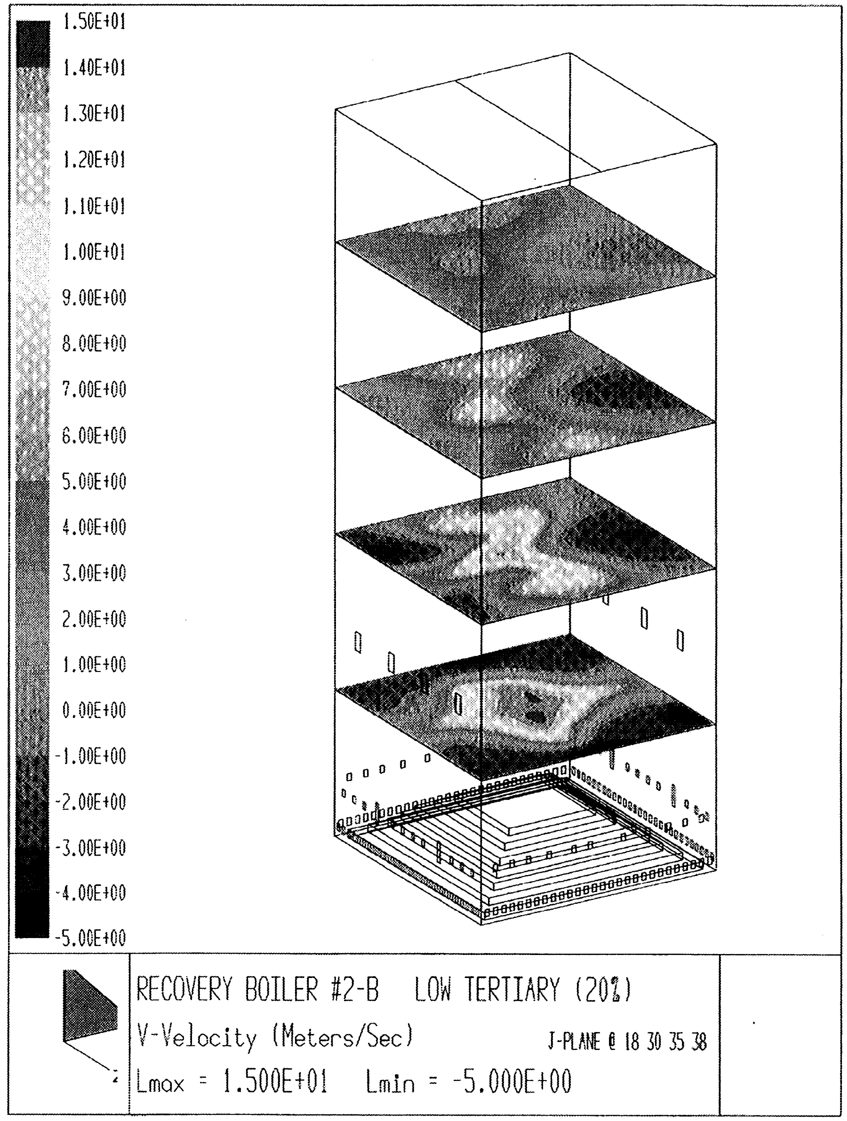

Figure 6 RB #2-B - Flow Field

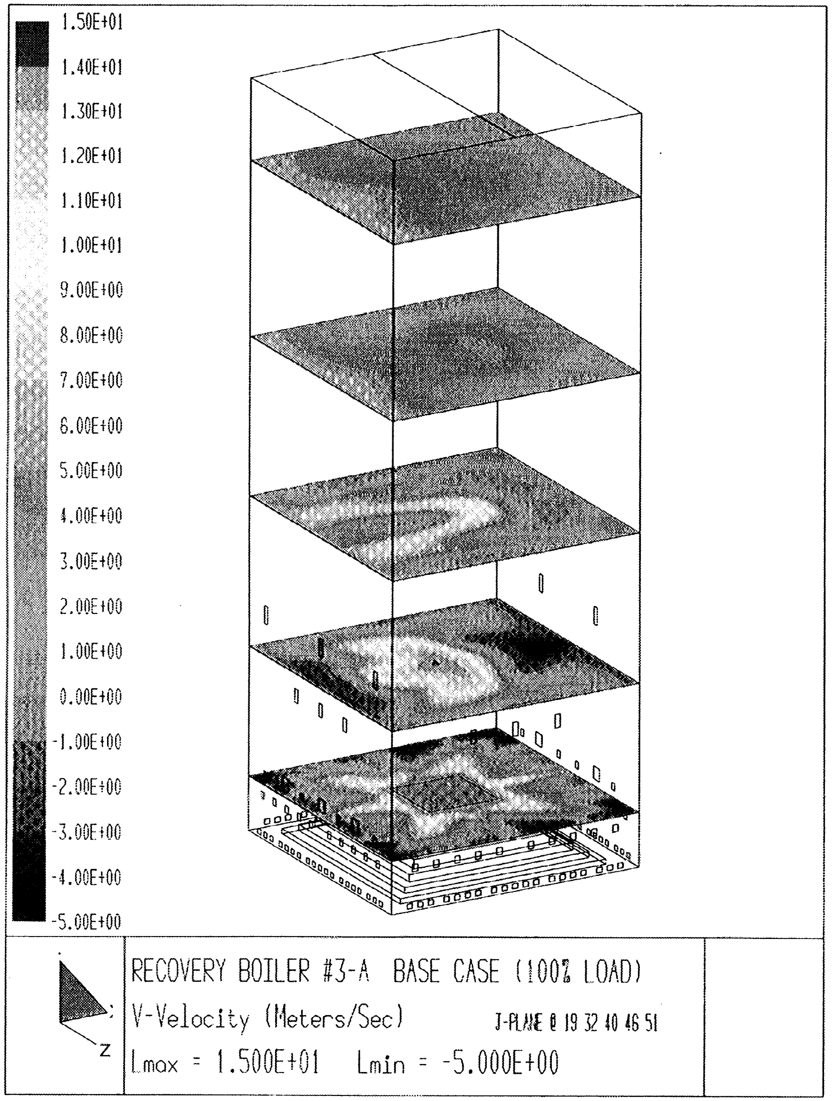

Figure 7 RB #3-A - Flow Field

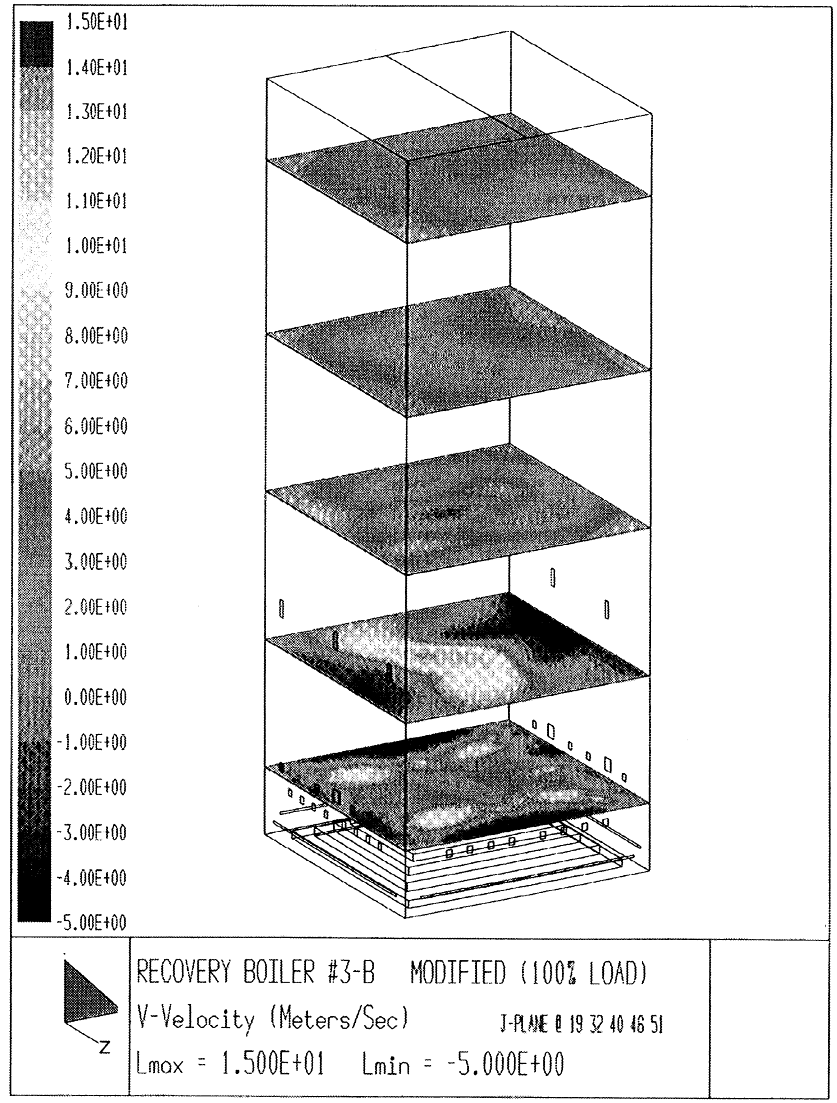

Figure 8 RB #3-B - Flow Field

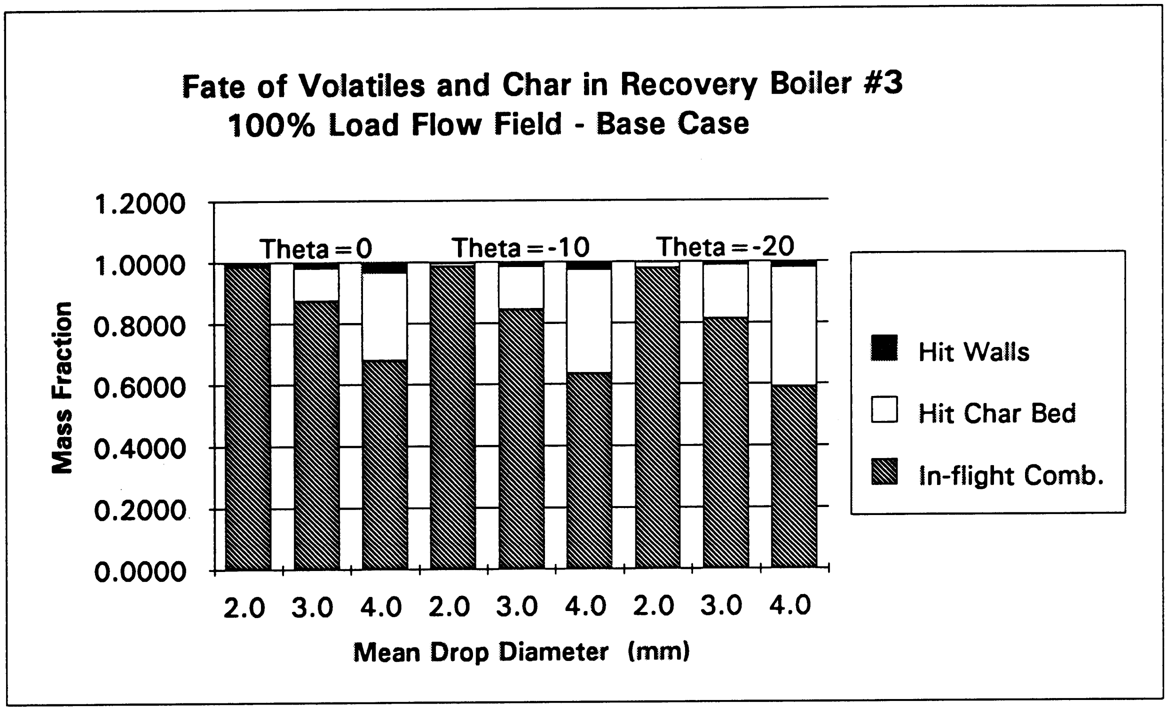

Figure 9 Distribution of Combustible Fraction of Black Liquor

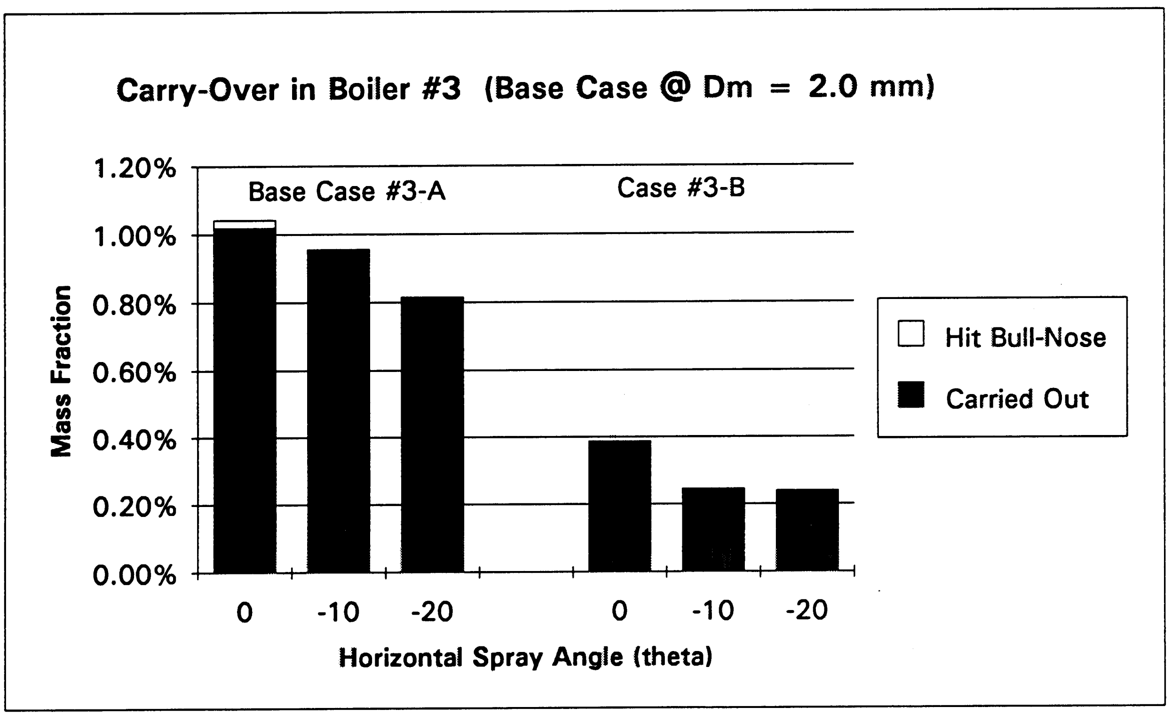

Figure 10 Carryover at 100% of Load (Dm = 2.0 mm)

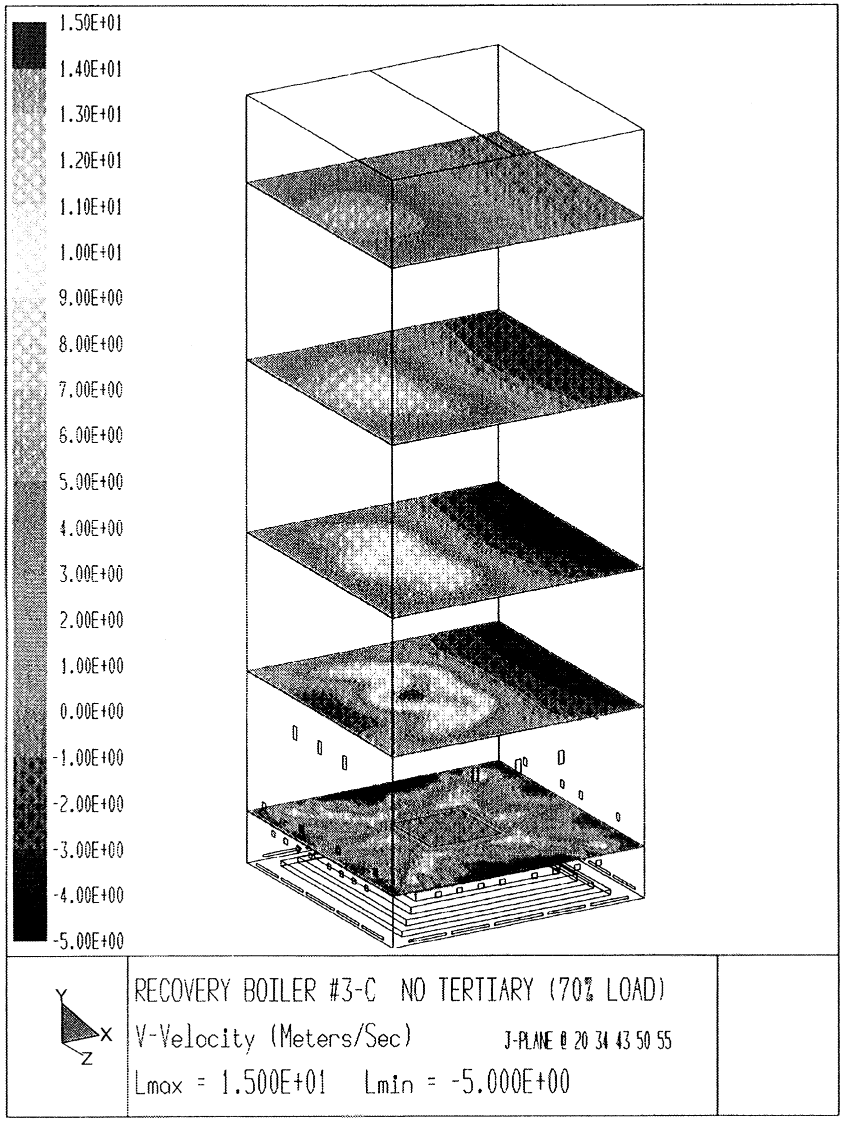

Figure 11 RB #3-C - Flow Field

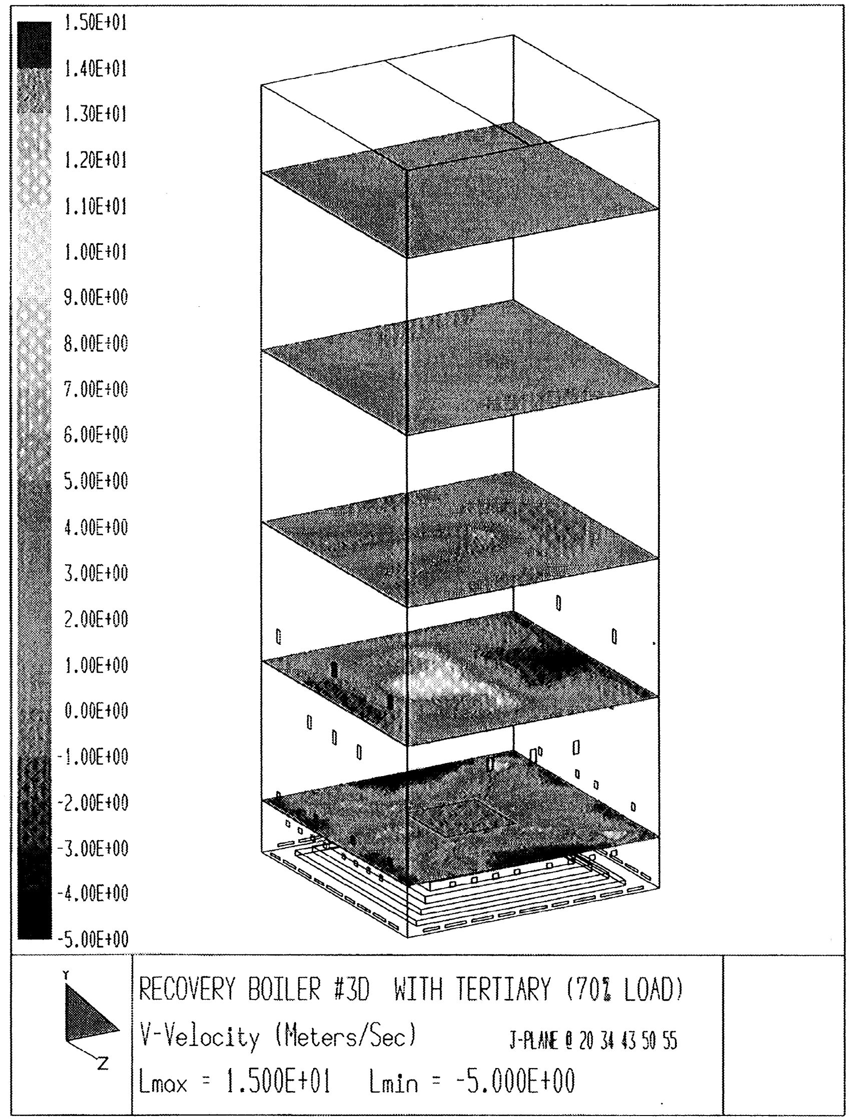

Figure 12 RB #3-D - Flow Field

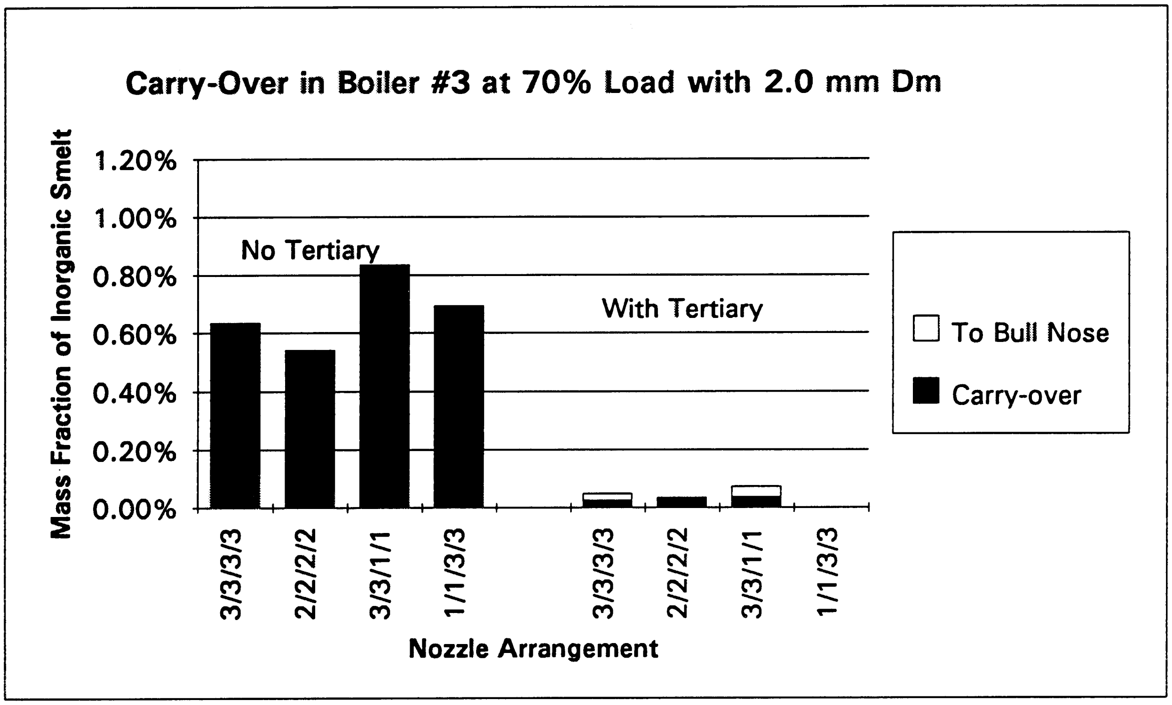

Figure 13 Carryover at 70% of Load (Dm = 2.0 mm)

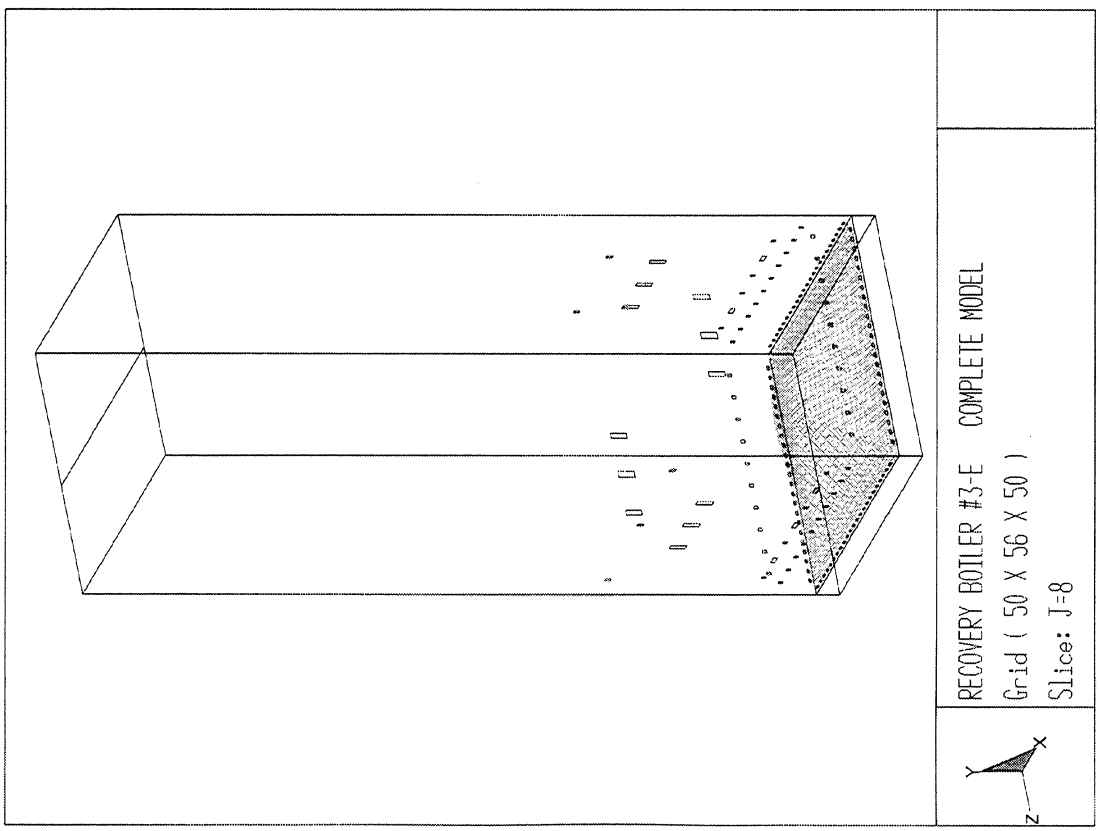

Figure 14 RB #3-E - Non-isothermal Grid

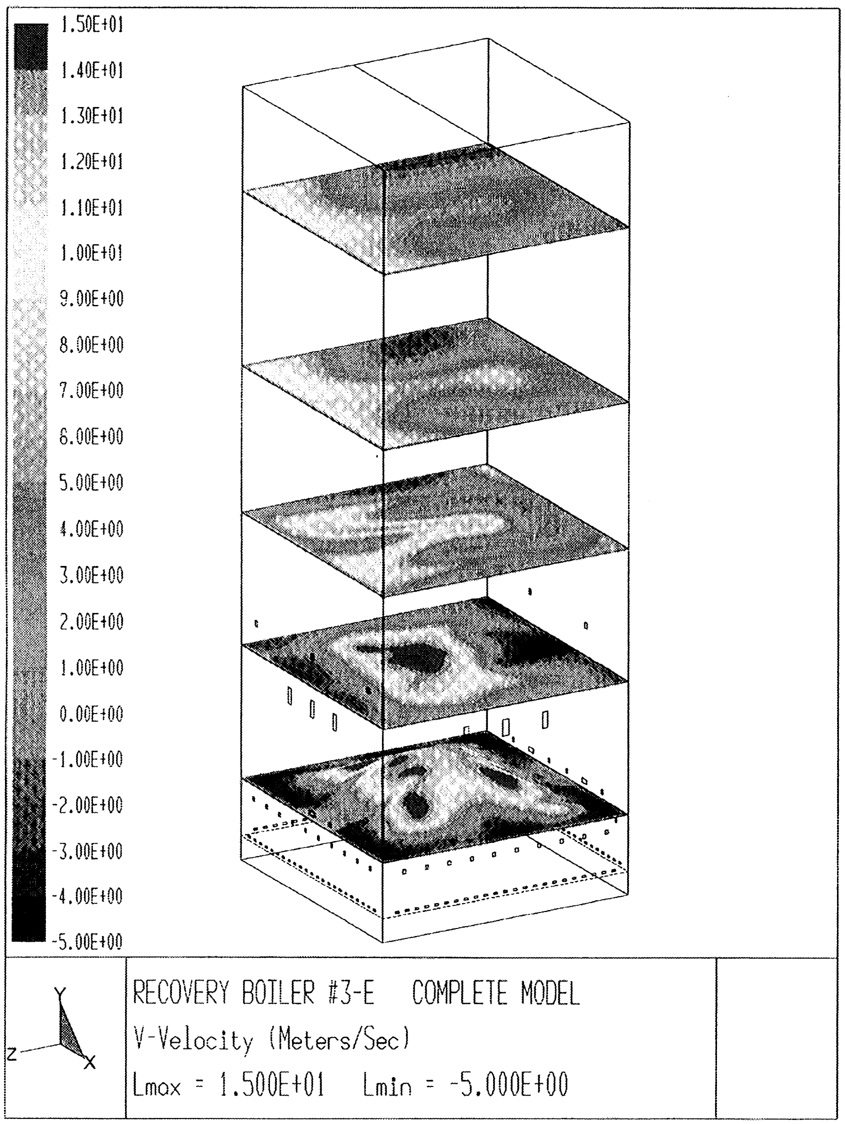

Figure 15 RB #3-E - Flow Field

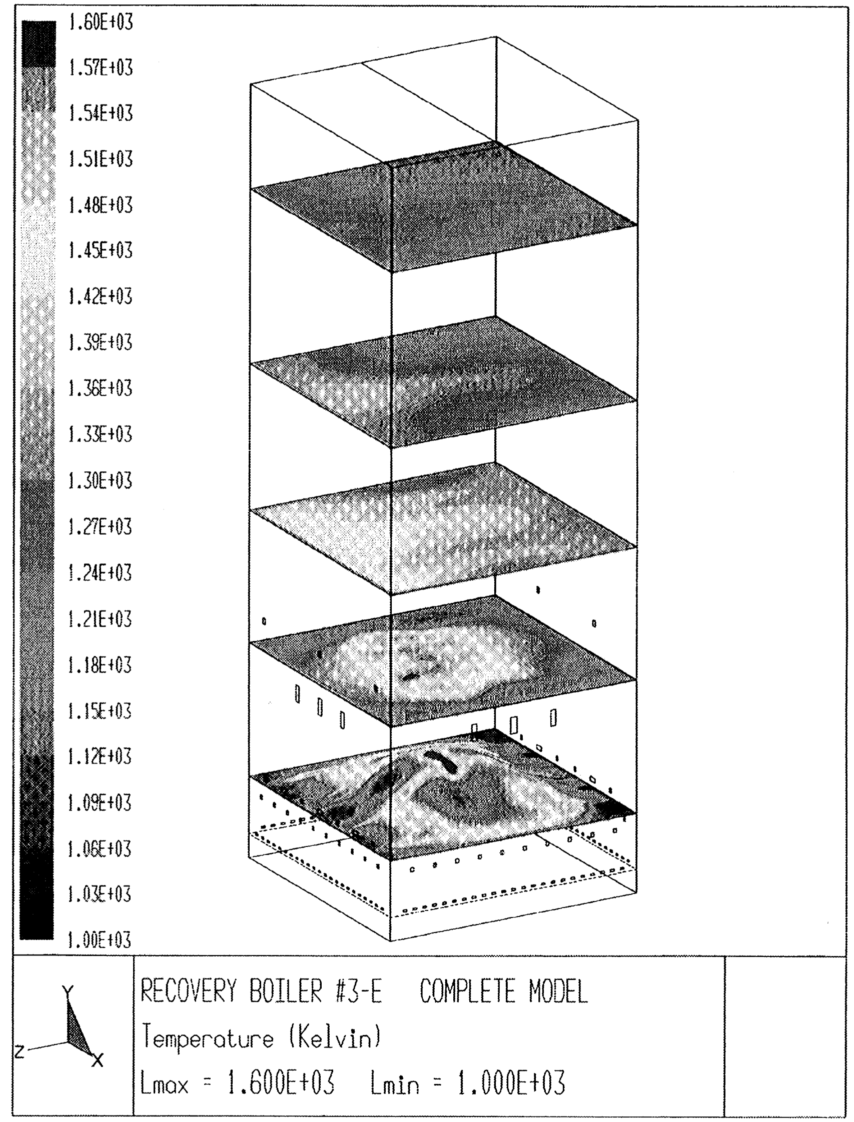

Figure 16 RB#3-E - Temperature